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Numerical Prediction of Wind-induced Internal Pressure on a Model Low-rise Building in Nigeria

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ABSTRACT— ***Wind normally induces both external and internal pressures on buildings which may cause great instability of structures. These induced pressures in turn contribute to the total wind load of the building. Appropriate prediction of this induced pressure can be found effective in the prevention of building failures. In this study, the prediction of wind-induced internal pressure on a model low-rise building in Nigeria was carried out by numerical analysis. The test was carried out on a computational model of a building using ANSYS FLUENT software. The Renormalization Group k-ε turbulence model was used to simulate wind impact on the building of size (2.78m x 2.43m x 2.30m) with a gable roof (slope 45°) at incident angles 90° and 45°. A comparative analysis was carried out to distinguish the effect of dominant openings and also the direction of the wind on the induced pressure. Results obtained from the tests were the values of pressure coefficients in the interior of the building which were used to characterize the induced internal pressure. Contours, tables and plots were used as graphical aids for the presentation of results. The inexpensive and less strenuous determination of wind induced pressure using computational fluid dynamics as portrayed in this work thus prove the effectiveness of numerical prediction as a precautionary method for the preliminary design of buildings.***

Keywords: Internal Pressure; Low-rise building; Numerical Prediction; Wind incidence angle.

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1. INTRODUCTION

The effect of wind on buildings cannot be over emphasized. The failure of a building is majorly determined by the action of wind against the structure which results in pressure differentials within and around the entire building. The influence of wind pressures on buildings are controlled majorly by the geometry of the building, angle of wind incidence, surroundings and wind flow characteristics (Amin and Ahuja, 2011). For both high- and low-rise buildings, wind loading is an essential dynamic loading of buildings. They are only of different magnitudes. In a country like Nigeria where there are more low-rise buildings than high-rise buildings, it is essential that wind loading of small structures is considered. Endo (2011) reveals that all structures (of all kinds of shape, size and materials) standing on the earth's surface are exposed to one or more types of extreme winds, and they are subjected to potentially catastrophic wind forces during periods of severe wind hazards.

Most windstorms have caused a wide range of damage to low-rise buildings such as residential houses, commercial and industrial structures. Such buildings and structures are frequently vulnerable to severe windstorms (Tieleman, 2003). The understanding of how load induced by winds act on low-rise buildings is an important step in being able to reduce such damages and this helps in providing reliable wind resistant design guidelines in building standards and codes (Endo, 2011). It will also motivate design of building of optimum ventilation.

Holmes (1978) reveals that internal pressures induced by wind on buildings have traditionally received much less attention than have external pressures. This is the case despite the fact that, for low-rise buildings in particular, the internal pressure loading may form a high proportion of total design wind loading on both structure and cladding.

There are many ways by which prediction of wind-induced pressures can be conducted. Wind pressure on buildings is expressed by pressure coefficients. The wind pressure coefficient is the difference in static pressure across the cap divided by the dynamic pressure of the wind.

$$C_p = \frac{P_x - P_0}{P_d} \qquad 1$$

Where $P_x$is the static pressure at a given point on the building façade[1] (in Pascal), P_0 is the static reference pressure (in Pascal), P_d is the dynamic Pressure (in Pascal). This paper investigated by computational methods, a prediction analysis for wind-induced pressure distributions of low-rise buildings in Nigeria thereby yielding a result that would be useful in taking absolute precautionary measures. Numerical prediction of wind loads by computational methods offers certain advantages over the use of scale models in boundary layer wind tunnels. For example, any Reynolds number, turbulence and boundary layer profile can be simulated. Numerical prediction also holds great potential for the extension codes of practice (Ahmad et al., 2011).

Wind-induced loads can be classified into external and internal loads. External wind-induced loads refer to the forces on the building as a result of the interaction of wind on the surface of the building. Internal loads, on the other hand, are as a result of the induced force cause by winds through envelope openings. The common openings basically include ventilation openings, breached doors and windows and leakages resulting from defects in construction and utility ducts. The combined effect of these pressures (both internal and external), at critical condition, causes the formation of extreme forces on building envelope which undermines the building envelope systems and components.

A number of literatures were found relevant to this study. Ahmad et al. (2011) obtained numerically the effect of wind loading on flat roof and pitched roof, and compared it with wind tunnel data. It was found that there is fair agreement between the numerical predictions and measurements for time-averaged wind loads on buildings.

An overview of pressure coefficient data was carried out by Cóstola et al. (2009). The complexity of pressure coefficient variation could not be wholly accounted for; therefore, Building Energy Simulation (BES) and Air Flow Network (AFN) programs were used to generally incorporate pressure coefficient variation in a simplified way. The two influencing parameters for which these differences are most pronounced are the position on the façade and the degree of exposure/sheltering. Results show that the comparison of the wind pressure coefficient data from different sources for sheltered buildings shows the largest differences, and data from different sources even present different trends.

Windstorm conditions generate internal pressure fluctuations through dominant openings, which may be created by impact of wind-borne debris. In his paper, Sharma (2009) discussed the importance of internal pressure, the physics of internal pressure dynamics, and the influence of various wind flow and building parameters on the characteristics of internal pressure.

Holmes (1978) presented a study of internal pressures in low-rise buildings using Boundary Layer Wind Tunnel (BLWT) for buildings with both windward and leeward[2] wall openings. The effect of inertia forces was examined by means of numerical simulation. And the fluctuating internal pressure resulting from external pressure fluctuations (due to wind turbulence) was also studied by using both numerical simulation and wind tunnel methods.

Castelli et al. (2012) performed a numerical simulation of aerodynamic loads acting on photovoltaic (PV) panels placed on roofs. After determining the influence of the incoming wind directions on the induced roof loads, a 2D analysis of the most severe load condition was performed, achieving a numerical quantification of the expected wind-induced forces on the PV panels on top of the roof.

Shiau and Chang (2008) discussed effects of building gap and wind attack angle on the characteristics of wind pressure for the inner face and front face of two buildings by performing measurements of the surface wind pressure statistical characteristics and pressure spectrum of two square buildings in side by side arrangement with various gaps and under different wind attack angles using a wind tunnel.

The characteristic of wind is defined by its pressure coefficient: mean and fluctuating pressure coefficients. The pressure coefficient is a dimensionless number which describes the relative pressures throughout a flow field. Every point in a fluid flow has its own unique pressure coefficient. Pressure coefficients can be determined during the testing of an engineering model at critical locations around the model and are used to estimate the effect of wind at those critical locations given some initial boundary conditions.

1.1 Motivation for the Study

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[1] The visible face of a building especially one which shows the most prominent architectural features

[2]Windward opening refers to that on the side from which the wind is blowing while leeward refers to the side sheltered from the wind

In Nigeria, the highest average wind speed is between 9 and 20 miles per hour (4 and 9 metres per second). However, windstorms can be as high as 56 miles per hour (25 metres per second), although they occur very rarely (Weather Spark, 2013). The effect of wind on buildings has long been underestimated and there have not been codes generated to predict internal pressures and their effects especially for low rise buildings which represent a high percentage of non-engineered or semi-engineered structures (Guha et al., 2011).

Aside from structural failures which are the common effects of excessive wind loads caused by induced pressures, ventilation requirement of a building is also affected by these induced pressures. Therefore, as stated by Ramponi and Blocken (2012), accurate CFD simulation of coupled outdoor wind flow and indoor air flow is essential for the design and evaluation of natural cross-ventilation strategies for buildings.

The application of numeric codes as a result of computational fluid dynamics (CFD) software has further reduced the complexity and stress in building testing for failure. Thus, a smart way of building long-lasting structures is in the application of CFD to model buildings to predict pressure concentrations and induced internal and external pressures before the final engineering of the structure.

Ever since the advent of CFD, developed nations in the world have been able to use this advantage to reduce the rate of building failures irrespective of the frequent windstorms and tornadoes especially in USA and China. This calls therefore for the introduction of these numerical predictions in Nigeria which will ultimately serve as a potential edge to other developing nations.

2. METHODOLOGY

The prediction of wind-induced internal pressure on a model low-rise building in Nigeria was carried out by numerical analysis. The commercial software ANSYS FLUENT 13.0 was utilized for the numerical simulation. FLUENT is an interactive, easy-to-use CFD software developed by the collaboration between Sheffield University and Creare Inc. for the wider engineering community. Its first version was launched in October 1983. It was acquired later by ANSYS, computer-aided engineering (CAE) Software Company, in May 2006. ANSYS is committed to the continued advancement of its technologies to deliver breakthrough capabilities with tools and functionalities to perform tasks easier and faster than before without sacrificing accuracy or quality, and the ability to capture and share knowledge, all in an open, flexible, scalable CAE environment (FLUENT, 2010). FLUENT offers a great advantage compared to the wind tunnel experiments. It holds great potential for extending codes of practice and its accuracy of predictions can be easily derived by balancing three things: the proper choice of boundary conditions, the accuracy of discretization methods and the proper choice of turbulence model (Ahmad et al., 2011). This explains why it was the chosen software for this research.

The low rise building model was of size 2.78m *L* x 2.43m *W* x 2.30m *H* with a gable roof (slope 45°). The model building was tested for two cases of dominant openings: a windward door (case A) and a windward door + a windward window (case B), for wind attack angles of 45° and 90°. The model was simulated for a test area of sparsely populated low-rise buildings. This is chosen to avoid boundary effects and also to find approximate results even for totally isolated buildings.

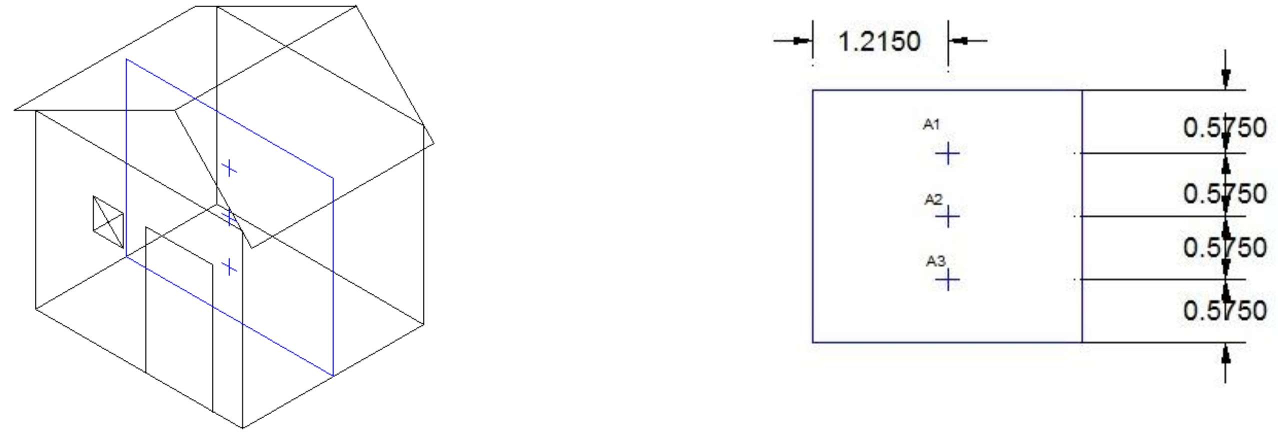
The governing equations were the Reynolds Averaged Navier-Stokes (RANS) equations, together with the Renormalization Group (RNG) k-ε turbulence model which was provided by FLUENT software. The k-ε model solves transport equations for the turbulent kinetic energy, k, and the rate of dissipation of turbulent kinetic energy, ε.

The computational domain (CD) was delineated using the Height (*H*) of the model building as a reference. The extension for CDwas vertically 5*H* above the roof of the model building, laterally 5*H* from the walls. For the flow direction, the extension of CDwill be 5*H* from front wall to the inflow boundary and 15*H* from the back wall to the outflow boundary to allow the flow re-development behind the wake region.

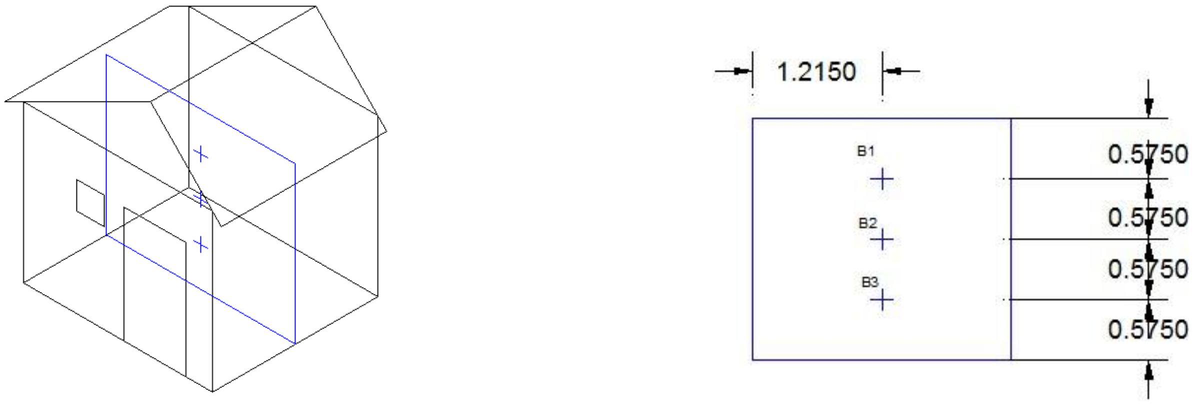
Fine grids made up of tetrahedral shaped cells were used to discretize the domain. And a measured inlet velocity profile of magnitude 21m/s with turbulence intensity of 25% and an integral length of 15m was applied to the whole upstream face of the CD. The upstream face of the CD is chosen as the velocity inlet and the downstream face, the pressure-outlet. A segregated pressure-velocity based solver was used in all the discretization schemes. Pressure interpolation was standard and second order upwind schemes were used. This is to achieve higher-order accuracy at cell faces through a Taylor series expansion of the cell-centered solution about the cell centroid. Values of pressure coefficients of internal points and building envelopes were extracted and plotted.

3. RESULTS AND DISCUSSION

At the pre-processing stage, certain points were defined to measure internal pressure coefficients. Figures 1 – 3 shows the building and the defined points of internal pressure measurements for each of the cases. The measured internal pressure coefficients are listed with the points in Tables 1 – 4 for each case of windward openings and also of wind angle of attack. A graphical display of the contours of external pressure coefficients for both 90^0 and 45^0 wind angles of attack are shown in Figures 4 and 5. The pressure coefficient each colour represents is shown in the colour chart by the left.

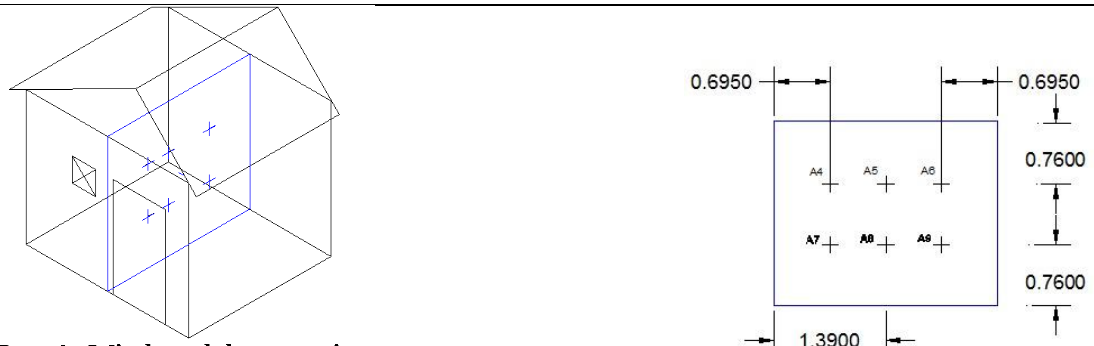


Case A: Windward door opening

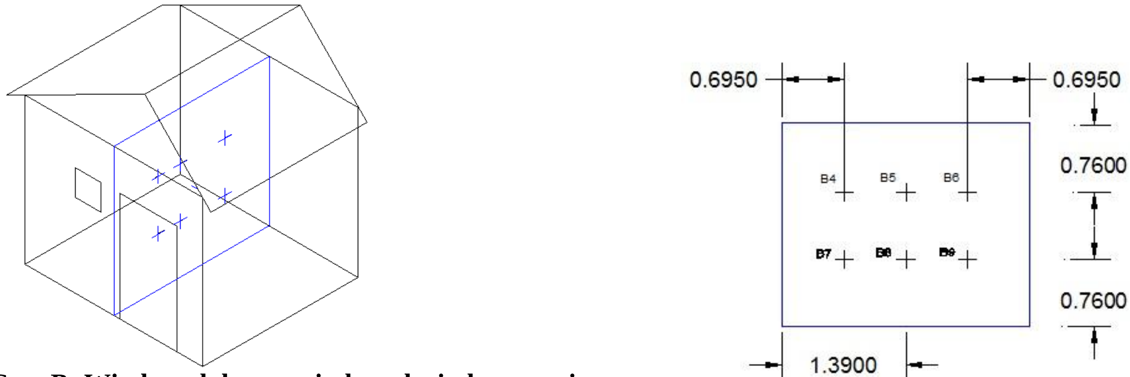


Case B: Windward door + windward window opening

Figure 1: Defined points for Internal Pressure Measurements (1)

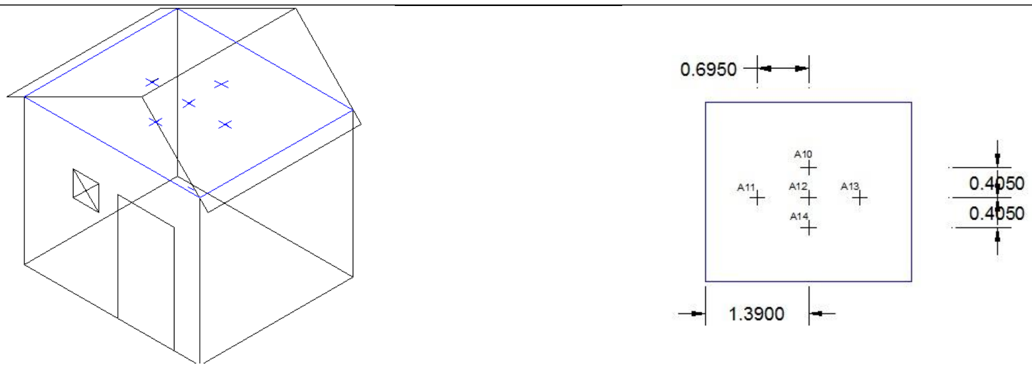


Case A: Windward door opening

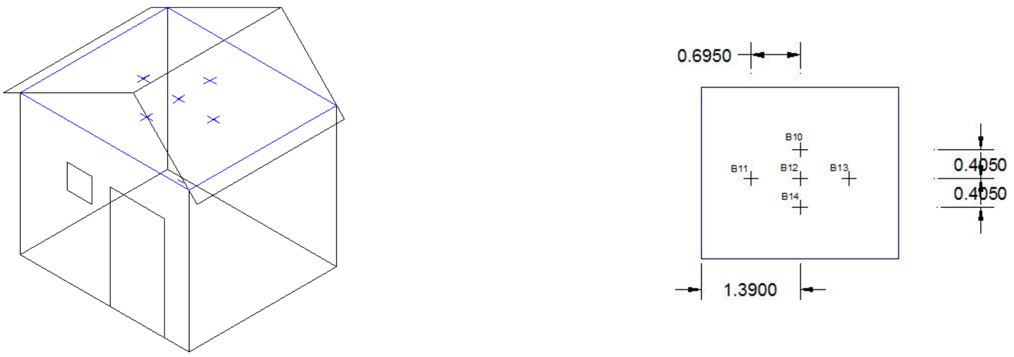


Case B: Windward door + windward window opening

Figure 2: Defined points for Internal Pressure Measurements (2)



Case A: Windward door opening



Case B: Windward door + windward window opening

Figure 3: Defined points for Internal Pressure Measurements (3)

Table 1: Internal Pressure Coefficients for Case A at 90^0 wind angle of attack

	Points	Internal Pressure Coefficients (values)
Inner room	A1	-1.078
	A2	-1.029
	A3	-0.951
	A4	-1.065
	A5	-1.070
	A6	-1.254
	A7	-1.061
	A8	-0.984
	A9	-0.825
Roof Ceiling	A10	-1.110
	A11	-1.090
	A12	-1.072
	A13	-1.043
	A14	-1.076
Internal walls	Back wall	-1.866
	Left wall	-1.077
	Right wall	-0.869

Table 2: Internal Pressure Coefficients for Case B at 90^0 wind angle of attack

	Points	Internal Pressure Coefficients (values)
Inner room	A1	-0.872
	A2	-0.832
	A3	-0.792
	A4	-0.870
	A5	-0.864
	A6	-1.098
	A7	-0.863
	A8	-0.803
	A9	-0.711
Roof Ceiling	A10	-0.895
	A11	-0.930
	A12	-0.880
	A13	-0.820
	A14	-0.876
Internal walls	Back wall	-1.891
	Left wall	-0.826
	Right wall	-0.719

Table 3: Internal Pressure Coefficients for Case A at 45^0 wind angle of attack

	Points	Internal Pressure Coefficients (values)
Inner room	A1	-0.924
	A2	-0.784
	A3	-0.665
	A4	-0.751
	A5	-0.872
	A6	-1.029
	A7	-0.750
	A8	-0.698
	A9	-0.544
Roof Ceiling	A10	-0.847
	A11	-0.924
	A12	-0.943
	A13	-0.812
	A14	-1.005

Table 4: Internal Pressure Coefficients for Case B at 45^0 wind angle of attack

	Points	Internal Pressure Coefficients (values)
Inner room	A1	-1.025
	A2	-0.921
	A3	-0.758
	A4	-0.782
	A5	-1.012
	A6	-1.241
	A7	-0.814
	A8	-0.797
	A9	-0.637
Roof Ceiling	A10	-0.985
	A11	-1.028
	A12	-1.077
	A13	-0.865
	A14	-1.101

In the similar work by Tecle et al. (2010), the internal and external pressure coefficients of a low-rise building were measured by both Wall of Wind (WoW) method and Computational Fluid Dynamics (CFD) Method. For wind angle of attack of 45^0 and 90^0, the similarity in contour of external pressure coefficient is as shown in Figure 6. Aside from the inlet velocity magnitude which was not specified in the paper, the same inlet properties are used for validation.

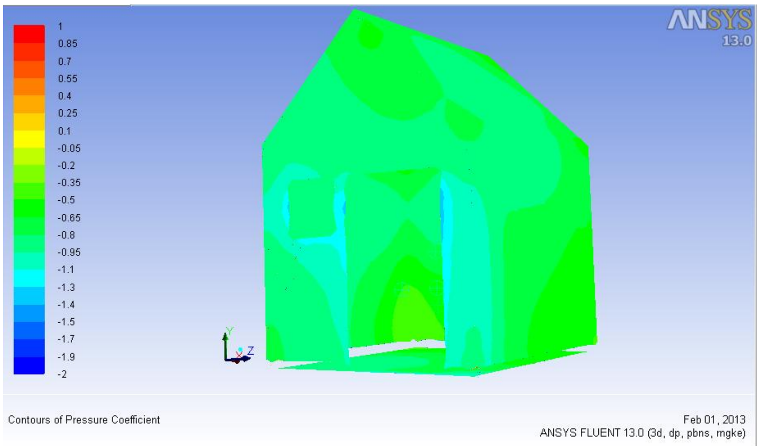


Figure 4: Contours of Pressure Coefficient (90^0 wind angle of attack)

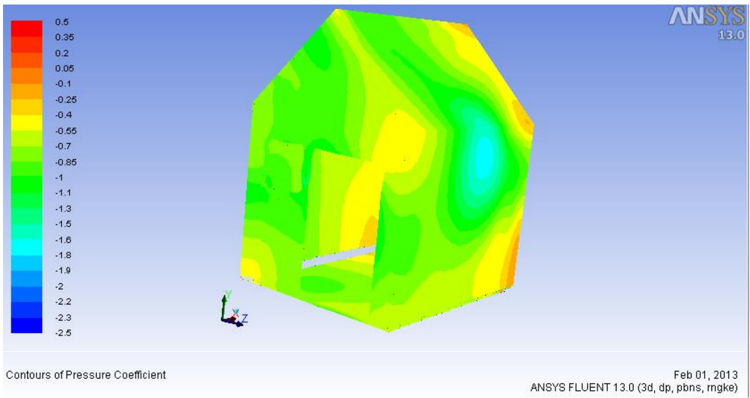
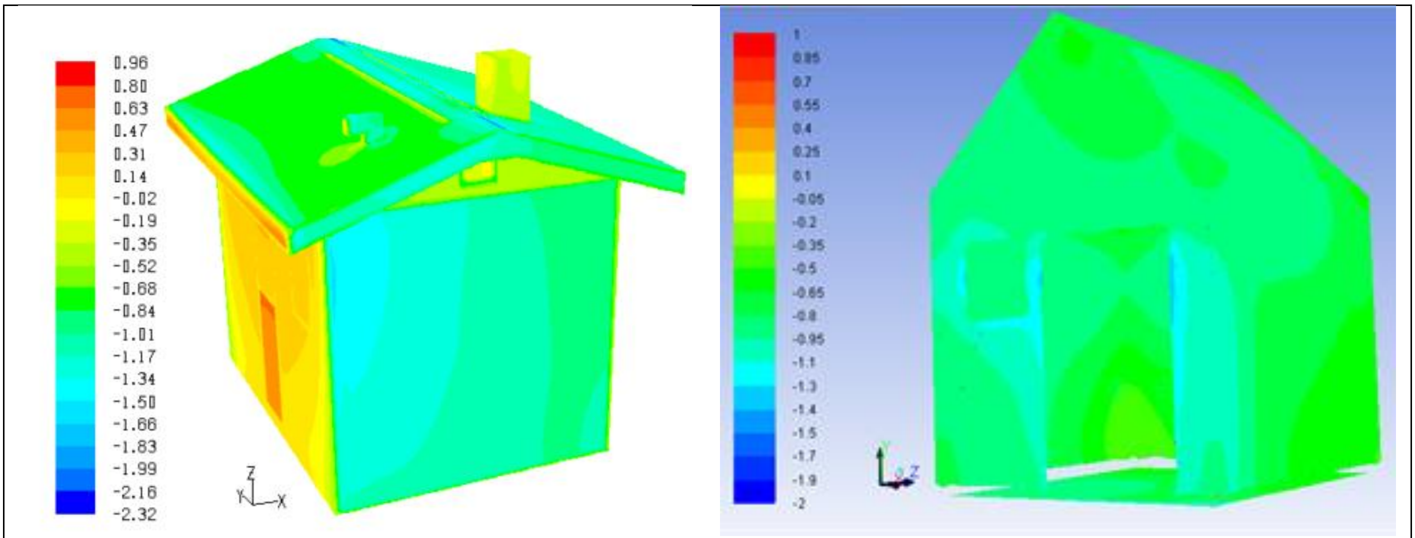
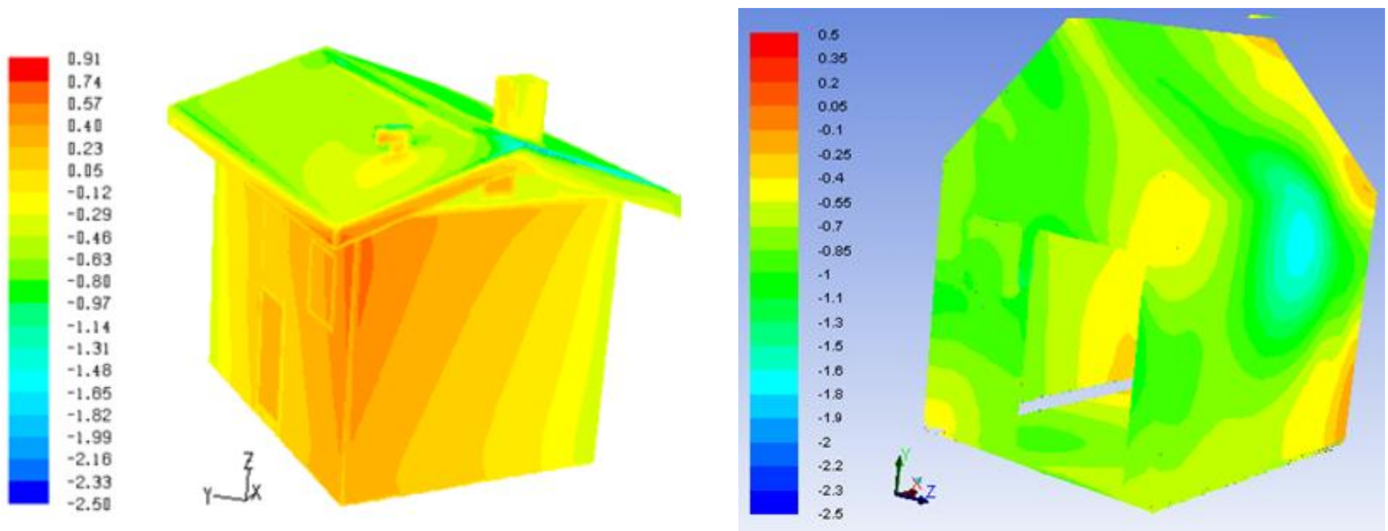


Figure 5: Contours of Pressure Coefficient (45^0 wind angle of attack)



Tecle et al. (2010) *CFD Result*

Figure 6a: External Pressure Coefficient for 90^0 wind angle of attack respectively in comparison with Tecle (2010)



Tecle et al. (2010) *CFD Result*

Figure 6b: External Pressure Coefficient for 45^0 wind angle of attack respectively in comparison with Tecle (2010)

When wind interacts with a building, both positive and negative (i.e., suction) pressures occur simultaneously. Wind striking a building can cause either an increase in the pressure within the building (i.e., positive pressure), or it can cause a decrease in the pressure (i.e., negative pressure). Internal pressure changes occur because of the porosity of the building envelope. Porosity is caused by openings around doors and window frames, and by air infiltration through walls that are not absolutely airtight. A door or window left in the open position also contributes to porosity (Smith, 2010).

Generally, both positive and negative pressures add to the wind load. Whereas positive pressures act towards the surface, negative pressures act away from the surface (ASCE, 2003). Positive internal pressure pushes up on the roof. This push from below the roof is combined with the suction above the roof, resulting in an increased wind load on the roof. It also pushes on the side and rear walls. Negative internal pressures pulls the roof down, which reduces the amount of uplift exerted on the roof. The decreased internal pressure also pulls inward on the windward wall, which increases the wind load on that wall (Smith, 2010).

The major effects of the internal pressures on buildings are found in the addition to wind load, air pollution in the enclosed room and improper ventilation. It is already established by internal pressures induced by wind result from the dominant openings and infiltration. Infiltration due to unintentional openings of as low as 1% porosity can change internal pressure coefficients associated with designed openings alone by orders of magnitude and even revise net internal pressures from positive to negative (Meroney et al., 1995).

4. IMPLICATIONS OF THE INDUCED INTERNAL PRESSURE

Wind induced internal and external pressures are major factors in the calculation of the total wind load of a building. Past research has indicated that internal pressure in a building is nominally induced by the wind through the external pressure field via three mechanisms: transmission through leakages in buildings, transmission through dominant openings like doors and windows and through flexibility of building envelope, with the most significant effects occurring in the presence of dominant openings (Guha et al., 2009).

When induced internal pressure exceeds a certain range of values specified for low-rise buildings as approved pressure coefficient ranges, failure of walls, roofs, doors or windows may occur. Concurrently, the comfortability of occupants in the building will be affected especially for buildings with passive ventilation forms.

According to Joseph and Minor (1977), internal pressure induced underneath a roof when a windward wall or wall component fails can produce an internal pressure coefficient of -0.8. Also according to the three basic design categories of internal pressures as defined by National Building Code of Canada (2005), the model type of this work (i.e. building dominant windward openings) falls in category three of -0.7 to +0.7 internal pressure coefficients. With the above, it can therefore be concluded that the result which shows internal pressure falling in the range of -0.7 to -1.1 is a deviation thus indicating that the effect of the wind flow into the building through the dominant windward openings is high. As a result, the presumed effects of high pressure coefficients will be experienced by the building.

5. CONCLUSION

The safety of a building structure in strong wind depends as much on internal pressure as it does on external pressure. As there is an inherent difficulty in reproducing internal conditions in a building, many studies based on mathematical models have been carried out to determine the influence of parameters such as external pressure, building volume, opening sizes and location of openings on fluctuating internal pressures in buildings.

The numerical prediction of wind induced internal pressure was carried out and it was found out that with extreme wind conditions modeled with high turbulence intensities, irregularly high internal pressure coefficients will be induced in the inner walls and roofs which would finally cause damage to the structure. Although openings in other walls of a building, such as side walls, can also produce internal pressure fluctuations of large magnitudes the windward opening is usually the critical design case (Holmes and Ginger, 2012), and this explains why this was the case study for this research.

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